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Colour and polarity contributions to global motion perception

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Abstract

The influence of the image segmentation cues based on colour and polarity on a motion coherence task were examined. In line with previous reports, when the signal and noise were given unique identities thresholds were much lower than when they were the same, suggesting a strong influence of segmentation. In another paradigm extra noise elements that differed in colour or polarity interfered despite this perceptual segmentation. We suggest that the results when signal and noise have unique identities are attributable to the subjects' ability to attend to a particular location(s) in space. When this strategy was eliminated by presenting the stimuli in the near-periphery or very briefly the effect of the colour or polarity information disappears.

1. Introduction

To what extent can non-motion cues (such as colour) contribute to the processing of motion information? This question has been asked a number of times, both in psychophysical and neurophysiological experiments, in consideration of whether motion detectors respond to chromatic information (Cavanagh & Favreau, 1985; Logothetis, 1991; Dobkins & Albright, 1993a,b; Logothetis, 1994; Morgan & Ingle, 1994; Cropper & Derrington, 1996). However there may be another way in which they may contribute. Colour is a most valuable aid to image segmentation (Mollon, 1989) and so might help our visual systems to combine information with similar chromatic properties whilst segmenting those with different properties.

A valuable tool in studying motion perception in recent years has been the 'global motion coherence' task, where pattern elements either move in the correct direction (termed signal) or in a random direction (termed noise) (Newsome & Paré, 1988; Snowden & Braddick, 1989). Sensitivity to motion can then be determined by the percentage of signal required to perform at a criterion level. In the light of the putative role of colour information in image segmentation outlined above we might expect that if we were to draw the signal elements in one colour and the noise elements in another colour then we could selectively process the signal elements, and thresholds should fall considerably. Indeed other cues to image segmentation might also be effective. For instance we might have all the signal elements lighter than the background whilst the noise elements are darker than the background (luminance polarity differences).

Croner and Albright (1994, 1997) have performed just such experiments and clearly demonstrate that thresholds fall in situations where the signal and noise differ in either colour or polarity. They suggest that this is evidence of how 'differentiation of a stimulus on one dimension will influence differentiation along another dimension'. However a report using only a slightly different technique appears to contradict this finding. Edwards and Badcock (1994) investigated the use of luminance polarity on a global motion task. Their displays consisted of a global motion coherence task where all the elements had the same polarity. To this they could then add extra noise dots either of the same polarity or of the opposite polarity. When the extra noise dots were of the same polarity they raised thresholds (as expected as they are indistinguishable from the other elements). Extra noise elements of the opposite polarity also raised thresholds, and by an amount equal to those of the same polarity, suggesting the motion system still processed them despite their perceptual segregation from the other elements. Ed-

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wards and Badcock (1996) went on to show a similar result for elements defined by colour.

There is, therefore a contradiction between these studies—those of Croner and Albright showing colour and polarity having a strong influence, whereas those of Edwards and Badcock showing no such influence. Following the intial reports of these results (Croner & Albright, 1994; Edwards & Badcock, 1994) we embarked on a series of experiments that attempted to replicate and discover why these differences occurred. Since the start of these experiments other reports have appeared that have had very similar ideas and experiments (Edwards & Badcock, 1996). However, as there is still much disagreement (Croner & Albright, 1997) we felt that our results might be still of some value, and, in particular two experiments to be reported here suggests a reason for the apparent discrepancy.

2. Experiment 1

We attempted to replicate the results of Croner and Albright (1997) for both colour and polarity segmentation.

2.1. Methods

Two-frame random dot kinematograms consisting of 800 elements (diameter 0.1°) per frame contained within a square of side 10 cm (5° from the viewing distance of 114 cm) were used. Each frame was presented for 250 ms (30 refreshes). Elements that would fall outside this area after displacement were 'wrapped' in a conventional manner. The elements could be red or green (simply defined as the output from the red and green guns of the monitor (Mitsubishi diamond Pro 20X—refresh rate of 120 Hz). The rest of the screen was dark (luminance = 0.01 cd/m^2). To eliminate non-colour cues to segmentation the red and green dots were initially perceptually matched for brightness and then each dot was given a luminance from a square distribution that was $\pm 30\%$ of the mean level.

As previous studies had differed in the speed/displacement of the elements we tested over a range of displacements from 0.025–0.4 deg arc. Five conditions were used:

Condition 1; signal was red, noise was red.

Condition 2; signal was green, noise was green.

Condition 3; signal was red, noise was green.

Condition 4; signal was green, noise was red.

Condition 5; signal was an equal mixture of red and green, noise was an equal mixture of red and green.

Similar experiments were performed using luminance polarity as a cue to segmentation. Here the background was set to 4.2 cd/m^2 and the elements were of mean luminance 0.5 cd/m^2 for the dark dots and of mean luminance 7.8 cd/m^2 for the light dots. Thus both light and dark dots had a Weber contrast ($\partial L/L_b$) of 0.84 where ∂L is the difference in luminance between the elements and background and L_b is the background luminance. It has been argued (Croner & Albright, 1997) that equating Weber contrast for the light and dark elements leads to different Michelson contrasts ($\partial L/(L_{max} + L_{min})$) for the light and dark elements which Croner and Albright then suggest may be responsible for the different pattern of results found in their own experiment and those of Edwards and Badcock (1994). We shall return to whether this is a feasible explanation of the results in Section 3.1. We would, however, like to note our preference for equating Weber contrast rather than Michelson contrast in patterns that are essentially sparse in nature (Moulden, Kingdom & Gatley, 1990).

After each presentation subjects gave a binary forced choice as to the direction of displacement (left vs. right). Percentage signal was manipulated from trial to trial via a QUEST procedure that ran for 64 trials for each condition. The five conditions were randomly interleaved within a block of 320 trials. Different speeds were run in separate blocks. Each measurement was repeated five times for RE and three times for MR. Subject MR was naive to the aims of the experiments.

2.2. Results

Our initial analysis looked to see if there were any systematic differences between the conditions that are conceptually the same (e.g. comparing the green signal, green noise with the red signal, red noise conditions etc.). Table 1 presents the differences between conditions 1 and 2 (same conditions) expressed in dB and averaged over the five displacement levels for both the colour and polarity experiments. There were no systematic effects. Table 1 also presents the differences between conditions 3 and 4 (different conditions). For one subject (RE) there appears to be a tendency for lower thresholds when the green elements were the signal, and when the dark elements were the signal (though this

Table 1
Difference in threshold (dB) averaged over all displacements

Condition	Subject	Green < red	Dark < white
Same	RE	0.06 ± 1.01	1.66 ± 2.28
	MR	2.00 ± 3.74	-0.08 ± 2.91
Different	RE	4.68 ± 2.46	4.72 ± 1.38
	MR	-1.72 ± 1.49	0.63 ± 1.09

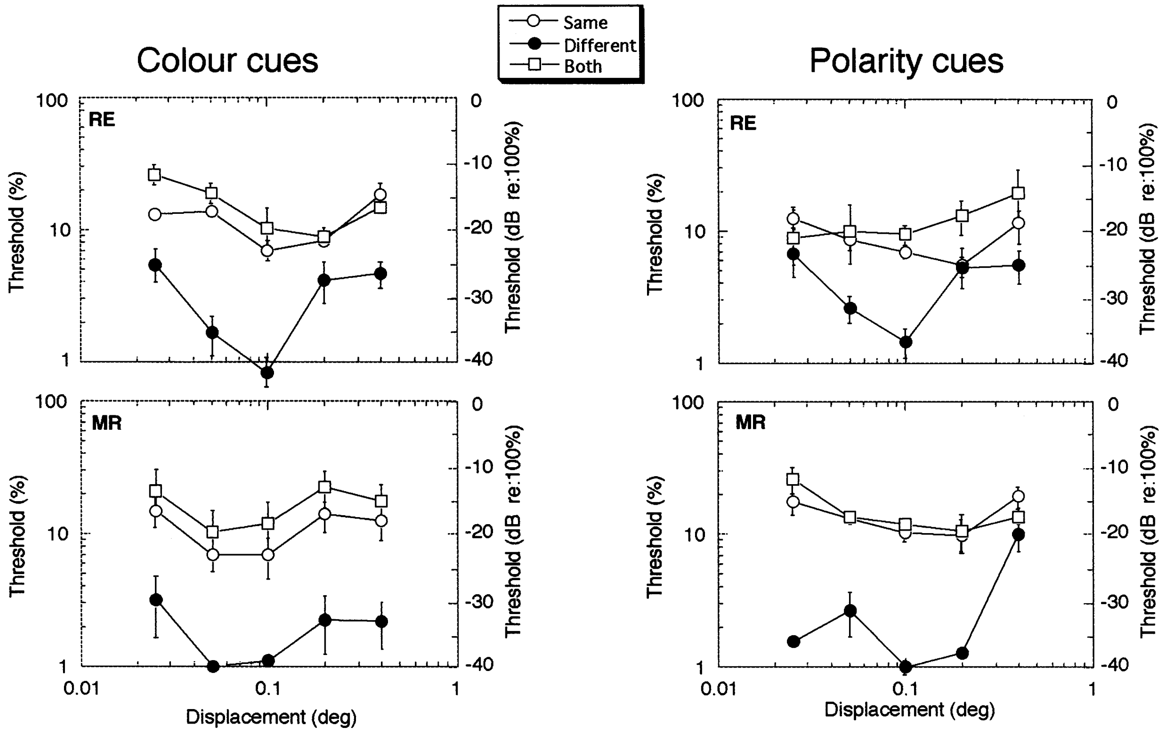

Fig. 1. Threshold signal to noise ratios are plotted as a function of the displacement of the test pattern for Experiment 1. The panels on the left are for the colour cues and those on the right are for the polarity cues. Open circles are when the signal and noise had the same colour/polarity, solid circles are when they had different colours/polarities and square for when the signal and noise were of mixed colours. Error bars shown are ± 1 standard error of the mean.

pattern of results was not shared by the other subject). However the effects were small and so we felt justified in pooling data across the two same conditions and across the two difference conditions. Thus the points presented in Fig. 1 are the mean and standard error of these pooled conditions.

In line with Croner and Albright (1997) we found thresholds fell by approximately 1 log unit when the signal and noise elements could be segregated on the basis of colour or polarity. This was true for all the displacement levels tested.

3. Experiment 2

This experiment attempted to replicate the findings of Edwards and Badcock (1994, 1996). The displays were similar in all respects to those of Experiment 1 save that the global motion coherence task consisted of 400 elements all of the same colour (or polarity). Six conditions were run:

Condition 1—red global motion coherence task.

Condition 2—red global motion coherence task

+ 400 red noise dots.

Condition 3—red global motion coherence task

+ 400 green noise dots.

Condition 4—green global motion coherence task.

Condition 5—green global motion coherence task

+ 400 green noise dots.

Condition 6—green global motion coherence task

+ 400 red noise dots.

Six similar conditions were run for the light/dark polarity cues. We also ran the experiment for three different displacement levels (0.05, 0.1 and 0.2°). Three subjects took part. RE from the last experiment, RS (the other author) and UP a naive observer.

3.1. Results

Once again we found no systematic effects of signal colour (or polarity) and so data were pooled across conditions 1 and 4, 2 and 5, and 3 and 6. The results are shown in Fig. 2. For the colour cue thresholds were increased equally by the addition of the extra noise elements whether or not they shared the same colour as the signal to noise ratio task. In the polarity task this was also true for subject RS. However, for subjects RE and UP, though the noise dots of a difference polarity

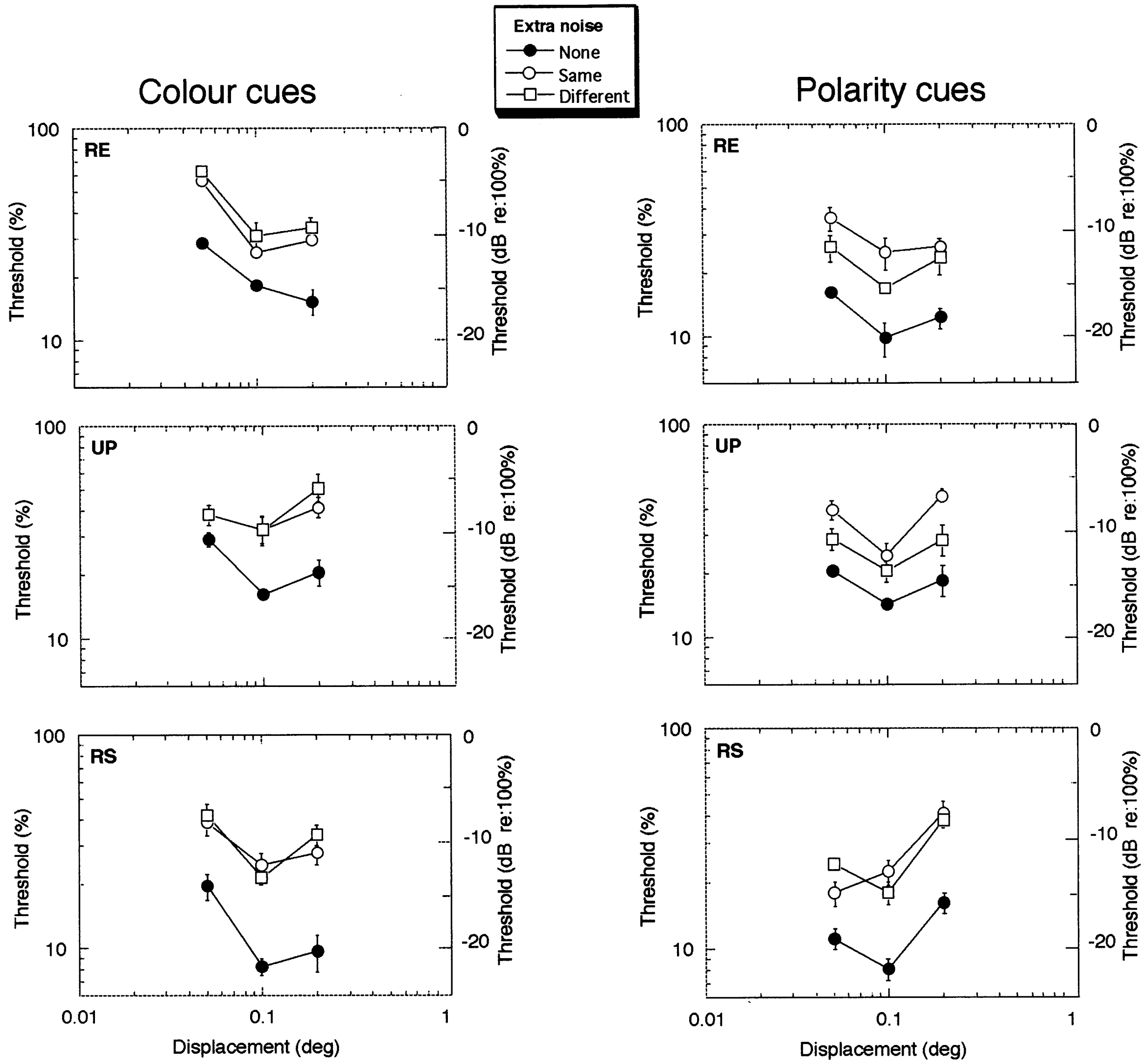

Fig. 2. Threshold signal to noise ratios are plotted as a function of the displacement of the test pattern for Experiment 2. The panels on the left are for the colour cues and those on the right are for the polarity cues. Solid circles are when no the extra noise was added, open circles are when the extra noise had the same colour/polarity as the motion task and squares are when the extra noise had different colour/polarity as the motion task. Error bars shown are ± 1 standard error of the mean.

did raise thresholds, their effect was not as strong as when the extra noise dots had the same polarity. Our results therefore replicate those of Edwards and Badcock (1994, 1996).

In attempting to find the reason for the apparent discrepancy between their own data and those of Edwards and Badcock, Croner and Albright suggested the use of Weber contrast (rather than Michelson-see Section 2.1) might mean that the dark dots were more salient than light ones. As Edwards and Badcock only report conditions where extra dark dots were added to a light signal to noise task they suggest that "the greater perceptual salience thus associated with the negative dots... enabled them to partially mask the positive contrast dots" (Croner & Albright, 1997). As they equated Michelson contrast in their own study they claim it did not suffer from this problem. In the present study we had a condition where extra dark dots were added to a light signal to noise ratio task, and a condition where extra light dots were added to a dark signal to noise ratio task. The data shown in Fig. 2 are pooled over these conditions. To check on asymmetries we also present data from these two conditions separately in Fig. 3. It can be seen that there is no consistent asymmetry in our data—light dots mask a dark signal to noise ratio approximately as much as dark dots mask a light signal to noise ratio task. Further the dot contrasts used in Experiment 1 and 2 were exactly the same yet the first experiment produces a large effect of polarity information whilst the second does not. Thus the explanation in terms of contrasts given by Croner and Albright to explain the differences between their own studies and those of Edwards and Badcock does not appear to be correct.

3.2. Discussion: Experiments 1 and 2

We have therefore replicated both the findings of Croner and Albright and those of Edwards and Badcock and, by using highly similar methodology and stimuli, rule out some trivial reasons for the discrepancy such as the displacement size, duration, luminance, contrasts etc. It appears that it is the two differing paradigms that produce the different results and therefore conclusions. We are left with the task of explaining this discrepancy.

Let us consider an extreme case where we had, say, one signal red dot and many green noise dots. In such cases the red dot would 'pop-out' and would automatically draw attention to itself (Joseph & Optican 1996)—or the subject might deliberately attend (covertly) to this location. If an attentional spotlight could be placed around this element then its signal-to-noise ratio would be very high (the exact level would depend on the size of the window and the density of neighbouring elements etc.—but in the extreme case there might be a single signal dot and no noise!) and hence good performance could be obtained. This strategy should be very good for the conditions where the 'odd-coloured' elements uniquely hold the motion signal and hence we can explain the results of Experiment 1. When many noise elements also have this colour the strategy should be less successful. In theory some advantage may still be drawn from the colour information, however it is clear that the advantage would be far less than when the colour uniquely predicts an area of high signal to noise ratio.

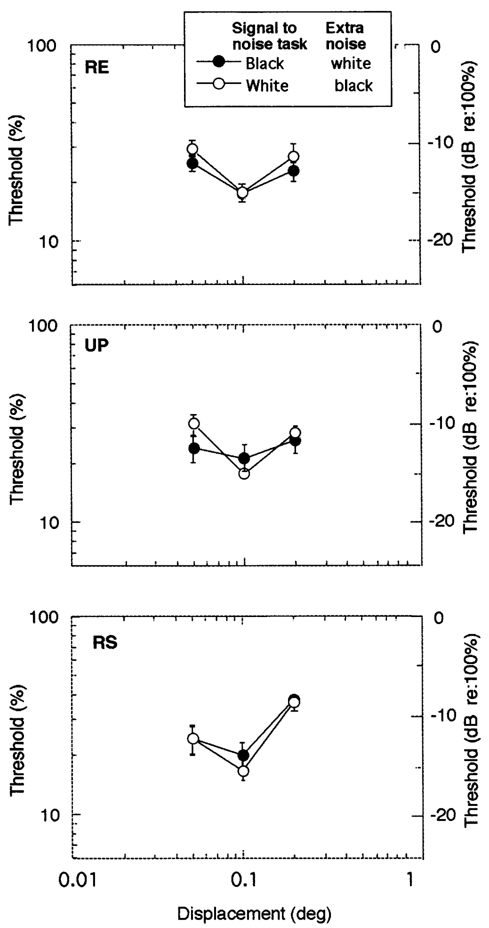

Fig. 3. As for Fig. 2 but showing separately the conditions under which light extra noise was added to a dark signal to noise ratio task (filled symbols), and when dark extra noise was added to a light signal to noise ratio task (open symbols).

A somewhat similar idea is expressed by Edwards and Badcock (1996) in relation to the Croner and Albright paradigm—"it may have been possible for the observer to identify and track the signal dots in order to determine the global motion direction". Our idea differs slightly in suggesting the narrowing of a spotlight of attention to a particular part of the field where the signal to noise ratio might be rather high, rather than an attention-based motion tracking (Cavanagh, 1992) of all the signal elements. In either case it is suggested that this mechanism is rendered less relevant when the signal and noise do not have a unique identity.

4. Experiment 3

We have suggested that the strong effect of colour/polarity cue seen in Experiment 1 is due to a narrowing of attention to a particularly salient and/or important part of the display. One way to reduce or eliminate this strategy would be to make sure the attentional window remains large. There are a number of lines of evidence that the attentional window is much larger in the peripheral retina than in the fovea (Humphreys, 1981; Shulman, Wilson & Sheehy, 1985; He, Cavanagh & Intriligator, 1997). We therefore predict that the effects of colour and luminance cues will be reduced or abolished in the peripheral retina.

4.1. Methods

We initially commenced this experiment by repeating Experiment 1 only with fixation on a LED positioned 7.5° underneath the centre of the stimulus. However we found a significant asymmetry between the conditions when we had red signal and green noise rather than green signal and red noise. This can be explained by the changes in relative colour sensitivity with eccentricity (Weale, 1953; Abramov & Gorden, 1977). We therefore performed pilot experiments where we fixed the luminance of the red gun and measured thresholds for green signal/red noise and vice versa for a range of green gun

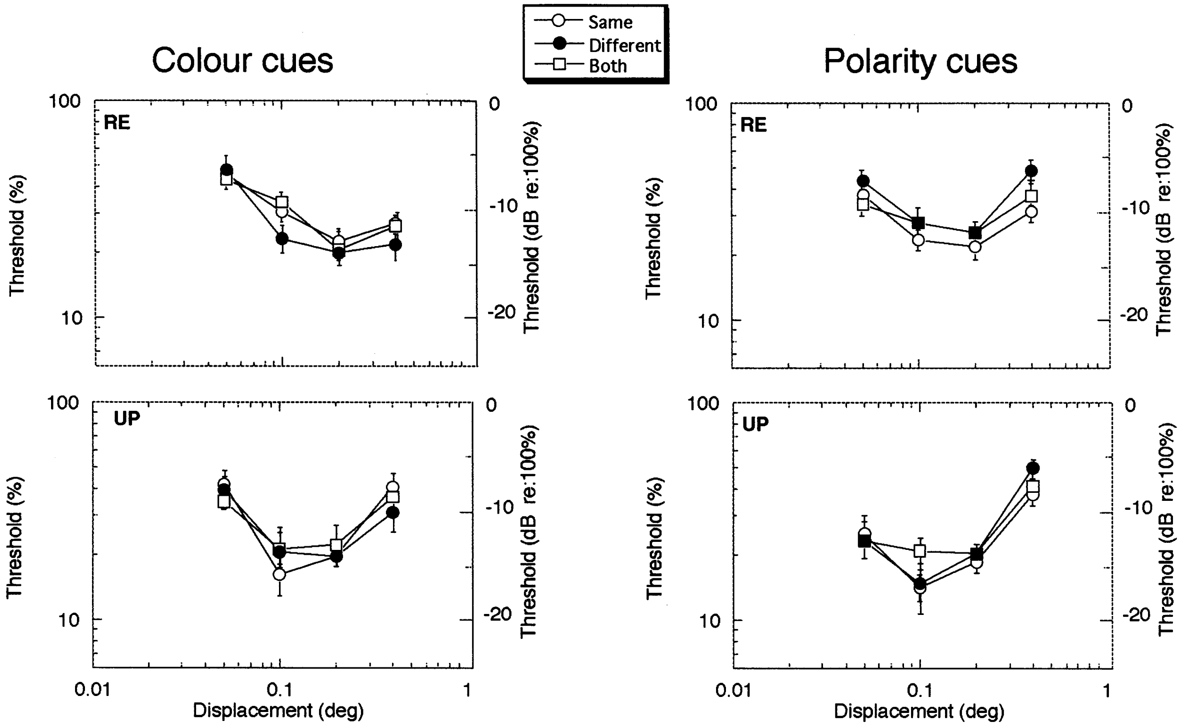

Fig. 4. As for Fig. 1 but showing the data from Experiment 3 where the stimulus was imaged 7.5° in the superior field.

luminances. In the main experiment we used the luminance of green gun that gave us equal thresholds in both conditions (set separately for each subject). This did not vary at the two displacement levels tested (0.05 and 0.2°) in the pilot experiments. For the experiments involving polarity these adjustments were not found to be necessary and hence this is a direct replication of Experiment 1 save for fixation 7.5° eccentrically.

4.2. Results

As in Experiment 1 the actual colour/polarity of the signal had no effect so results for conditions 1 and 2 (signal and noise same colour or polarity), and for conditions 3 and 4 (signal and noise different colours or polarities) were pooled. The results are plotted in Fig. 4. It is now apparent that there were no differences between the conditions.

4.3. Discussion

The results of Experiment 3 are consistent with the predictions made if increasing the eccentricity of viewing widened the window of spatial attention needed to selectively process a small subset of the elements. Unfortunately, however, changes in eccentricity also have other effects that might influence the results. Colour perception changes with eccentricity (as mentioned in Section 4.1 along with how we attempted to compensate for this) and whilst we still had the phenomenology of red and green perceptual segregation it is unclear that this would be relevant to the motion processing pathway. It may also be possible to construct similar arguments for changes in polarity perception due to the changes in size and density of on- and off-centre ganglion cells across the retina (Dacey, 1994). Sensitivity to motion also changes with eccentricity, with particular loss of sensitivity to slower speeds (van de Grind, van Doorn & Koenderink, 1983). However, our findings of a lack of interaction of the effects of colour/polarity segregation and speed of movement for both foveally and peripherally presented patterns, appear to make this an unlikely source of difference between the experiments. So it is possible that these changes, rather than those to do with spatial attention, may explain the present results.

Given our arguments it should be possible to reinstate the effects of colour/polarity segregation even for the eccentrically viewed stimuli by appropriate spatial scaling of the stimulus[1]. Unfortunately we have no a priori idea of what this spatial scaling should be. Whilst studies have shown that the size of the ‘attentional window’ increases with eccentricity they do not give general formulas for the exact size or the rate of increase that might be applied to other situations (Shulman, Wilson & Sheehy, 1985). Indeed this may be unwise as it is clear that even for a particular stimulus, task type (sensitivity versus reaction time) seems to

[1] Our thanks go to an anonymous reviewer for this suggestion.

determine the size of the attentional window (Handy, Kingstone & Mangun, 1996). Thus the size of the attentional window may vary considerably depending on stimulus, task etc. What is clear is that the attentional window is far greater than mere spatial resolution, and that its fall off with eccentricity is more drastic (He, Cavanagh & Intriligator, 1997). Further, manipulations of spatial size, density etc. do not overcome the other objections raised in the previous paragraph. Nevertheless we attempted some pilot experiments to see if we could reinstate the advantage conferred by colour information by altering either dot density and/or spatial scale. At a given displacement size (0.1°) we reduced the dot density by a factor of eight but still found no effect of colour information. We then tried scaling all spatial dimensions by a factor of four by viewing the screen from 28.5 cm instead of the usual 114 cm (displacement size remained 0.1° by appropriate adjustment of parameters). We once again found no effect of colour information if the nearest part of the image was 7.5° from fixation (if the central part was 7.5° from fixation the pattern now encroached upon the foveal field and a strong effect of colour information returned). Hence our attempts to reinstate the effect for purely peripheral stimuli failed. This may, of course, be due to the 'spatial attention' hypothesis being wrong, but we fear that this approach has limited merits due to a lack of knowledge about how the scaling should be done. Instead we reasoned that the opposite approach might prove more fruitful—it should be possible to eliminate the effects of colour information for foveally viewed stimuli if attention can be appropriately manipulated. This approach neatly side-steps the problems outlined above in trying to compare foveal and peripheral stimuli.

5. Experiment 4

Many experiments on spatial attention have employed a 'cueing' paradigm where information about the likely location of a target is presented (Posner, 1980). A consistent finding is that this cue must precede the target by a small amount of time. For a cue that automatically draws attention to itself (an exogenous cue) the cue must precede the target by at least 50 ms with the size of the cueing effect increasing up to around 150–300 ms (Müller & Rabbit, 1989; Nakayama & Mackeben, 1989). This presumably reflects the time taken for the 'window' of attention to move or focus upon the appropriate point in space. We therefore argue that if we restrict the amount of time available to process our random dot kinematograms we should find that the colour information is less useful (and maybe useless) for the briefer presentations.

5.1. Methods

These were exactly as for Experiment 1 save that the displacement used was always 0.1° and that the duration of the random dot kinematograms (RDK) were either 83, 166 or 332 ms. Each RDK duration was run in a separate block of trials. Two different experiments were performed. In the first we immediately followed the presentation of the RDK with a masking noise pattern that consisted of a set of 800 dots (400 red, 400 green or 400 light, 400 dark as appropriate) randomly positioned over where the stimulus had occurred. This was employed so as to limit any further processing of the display. In the second experiment this masking pattern was omitted. For both experiments there were four conditions interleaved within a block of trials corresponding to the first four conditions of Experiment 1. Each measurement was repeated three times. As there were no systematic differences between conditions 1 and 2 (the signal and noise in the same colour/polarity) or between conditions 3 and 4 (the signal and noise in different colours/polarities) data were pooled. Therefore each data point of Figs. 5 and 6 represents the mean and standard error of six measurements. Two observers took part, one naive (ST) and one of the authors (RS).

5.2. Results

Results from two subjects are plotted in Fig. 5 for the colour manipulations, and in Fig. 6 for the polarity manipulations. The upper panels are for the experiments where the RDK was immediately masked by the noise pattern, whilst the lower panels are for the RDKs that were not followed by this mask pattern. For both conditions we find that the data when the signal and noise had the same colour /polarity (filled symbols) or when it had different colour/polarity (open symbols) were very similar for short duration RDKs but performance was much better when the colour/polarity information was available in the longer duration RDKs. The data point at 333 ms for RS in the different condition of the polarity manipulation is omitted as thresholds fell to such a level that the subject could still perform well even when only one signal dot was present and so no sensible measure of threshold could be obtained.

5.3. Discussion

The results show that the effects of colour information are dependent upon the duration of the RDK. There is little or no effect of colour information for very short durations, but a large effect at longer durations. This is the pattern of results predicted if spatial attention were to take some time to locate the salient elements in order to discover their motion.

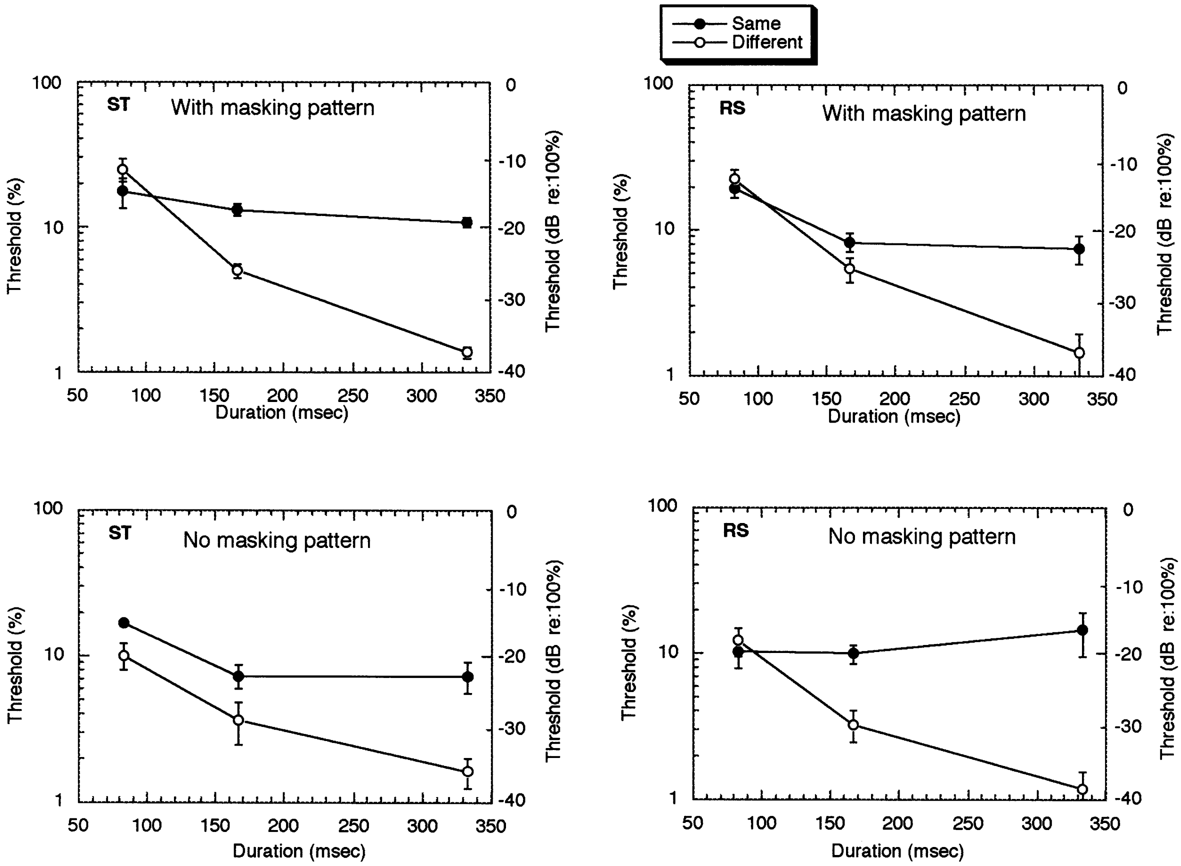

Fig. 5. Thresholds are plotted as a function of the duration of the frames of the random dot kinematogram with (open symbols) and without (filled symbols) the colour information. The upper panels are for the experiments where the display was immediately masked by extra noise dots, the lower panels are for those where these were omitted. Error bars shown are ±1 standard error of the mean.

6. General discussion

We have successfully replicated both the findings of Croner and Albright (1994, 1997) and those of Edwards and Badcock (1994, 1996). We have suggested that the technique of assigning unique identities (colour or polarity) to the signal elements might allow for an attentional strategy in which subjects selectively process information at a location identified by appropriately coloured element(s) (Shih & Sperling, 1996) and hence improve performance. Two manipulations thought to compromise this ability eliminated this effect of colour information even when using the paradigm of Corner and Albright. Moving the stimuli to peripheral locations (thought to increase the size of an attentional window) or reducing the duration of the RDK (so that spatial attention did not have time to focus upon a salient area) both produced motion coherence thresholds that were unaffected or much less affected by the colour/polarity manipulations.

Since we first submitted this paper a similar idea concerning the effects of spatial attention in the Croner and Albright paradigm has been reported (Roitman & Shadlan, 1997). They show that a spatial cue that precedes the motion of the dots but indicates the position of the moving dots also lowers thresholds in a manner similar to the colour cues used here. Their results and ideas appear entirely consistent with those proposed here. This also adds to the increasing evidence that spatial attention is important in determining motion and speed thresholds in psychophysical tasks (Blakemore & Snowden, 1997), and can also effect neuronal processing in areas thought to be concerned in such tasks (Treue & Maunsell, 1996).

The suggestion of Edwards and Badcock (1996) that an 'attention-tracking' system might be the responsible for the effects in this paradigm also shares many similarities with our idea. However it is not clear why an attention-tracking system should fail in the near-periphery as other experiments (Pylyshyn & Storm, 1988) have shown that we can successfully track several items over a screen subtending over 20°.

We have described the hypothesised attentional processes as a spatial window. However much recent evidence suggests that attention can also be characterised as 'object-based' under many circumstances (Duncan, 1984) including those of cueing paradigms (Egly, Driver & Rafal, 1994). To this end we might imagine that in

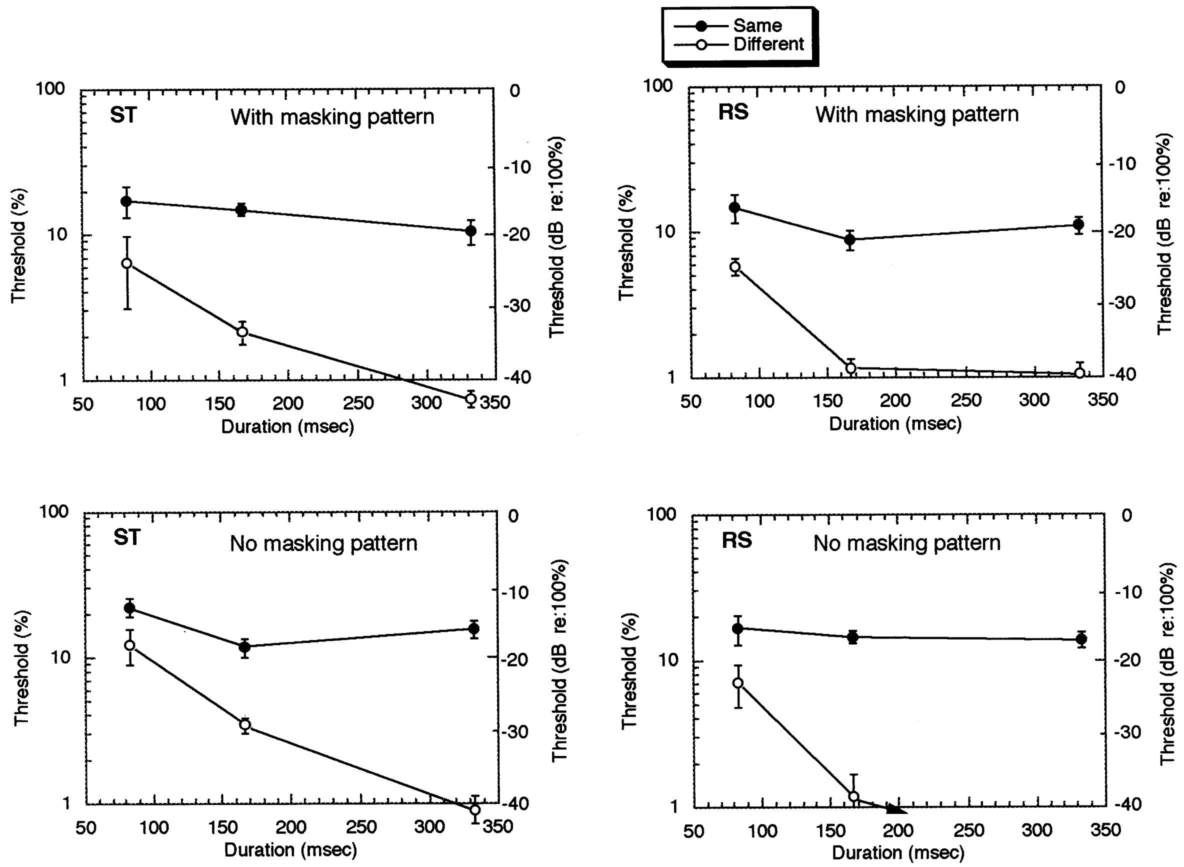

Fig. 6. As for Fig. 5 but using polarity information instead of colour.

the displays we have used the 'red dots' might form one perceptual object and the 'green dots' another perceptual object. One might then 'pay attention' to the red object (or at least give information from this object greater weight in any motion calculation). This idea is now very similar to that advanced by Croner and Albright themselves. However it is unclear as to why such a strategy would not produce some improvement in the 'extra noise' paradigm of Edwards and Badcock. At the moment not much is known about when and where spatial or object based attentional strategies are employed. Recent work in our laboratory (Snowden, in preparation) seems to suggest that space-based attentional mechanisms have a faster time course than object-based ones. Clearly greater understanding of these mechanisms might help further in understanding of the differences between the results found in Experiments 1 and 2 of this study.

If our explanation is accepted then we are drawn to the conclusion that our motion system (at least the part responsible for global motion coherence thresholds) can not selectively process all the elements of a particular colour or polarity to the exclusion of all other elements. This is not to say that other aspects of motion processing can not be influenced by colour (Møller & Hurlbert, 1997), or that attention to colour can not influence other judgements (Brawn & Snowden, 1997, 1998) or that other cues to image segmentation will produce similar results (Snowden & Rossiter, 1998).

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